



Energy auditing and carbon footprint under long-term conservation agriculture-based intensive maize systems with diverse inorganic nitrogen management options

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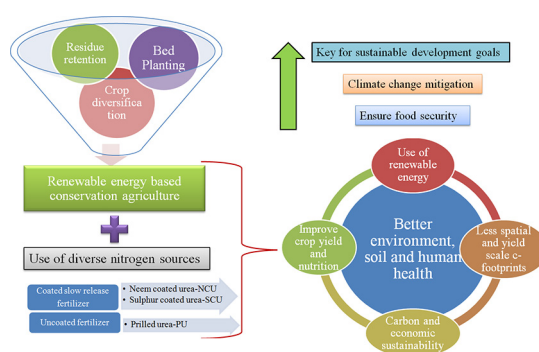
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HIGHLIGHTS

- Coated N fertilizer in CA enhanced yield and profitability with lower C-footprints.
- Neem coated N fertilizer had higher B:C ratio, system yield and C-efficiency ratio than PU.
- MMuMb rotation has ~11% higher B:C ratio, higher net energy and ~9% less C-footprint on spatial scale.
- MWMB has higher C-input with lower C-efficiency and C-sustainability index than MMuMb.
- CA + NCU based MMuMb system, an environmentally safe and energy efficient technology

GRAPHICAL ABSTRACT



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ABSTRACT

A greater energy grant in diesel-fed machinery driven farming substantiate the higher GHGs emission along with improper input (fertilizer, pesticide and irrigation) use and intensive soil management. Practicing conservation tillage, residue retention and diversified crop rotations were advocated because of their multiple benefits. Hence we explored the energy requirement and carbon footprint of conservation agriculture (CA) based maize production systems. Coated N fertilizer [sulphur coated urea (SCU) and neem coated urea (NCU)] were compared with unfertilized and uncoated prilled urea (PU) in the scenario of with and without residue retention on permanent beds (PB) under diversified maize systems [MMuMb, maize-mustard-mungbean and MWMB, maize-wheat-mungbean] in search of a sustainable and energy efficient production system with lesser C-footprint. Results of the 4-year study showed that crops planted on permanent bed with crop residue (PB+R) registered 11.7% increase in system productivity compared to PB without residue (PB–R). N management through Neem coated urea (NCU) recorded 2.3 and 10.9% higher system productivity compared with non-coated prilled urea plot under PB–R and PB+R, respectively. MMuMb was marginally superior than MWMB system in terms of cropping sequence yield, profitability, and energy and carbon use efficiency. Crop residue retention in zero tilled

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PB increased cost of cultivation by 125 and 147 USD/ha in MMuMb and MWMB systems, respectively. The quantified carbon footprint value was higher in MWMB system. In CA-based practices, crop residues management contributed the highest energy input (61.5–68.4%) followed by fertilizer application (17–20%). Among N management practices, neem coated urea (NCU) significantly improved system productivity and profitability in all the residue applied plots compared to un-fertilized and prilled urea (PU) applied plots. Similarly, higher energy output was also observed in NCU treated plots. However, carbon footprint value was higher in PU (268–285 CO₂-e kg/Mg) plots than NCU (259–264 CO₂-e kg/Mg) treated plots. Thus, the study supports and recommends that the CA-based MMuMb system with efficient N management through NCU is an environmentally safe, clean and energy efficient one, hence can reduce carbon footprint, will ensure food security and will mitigate climate change.

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1. Introduction

The rights for a cleaner environment for the successor on the planet have been vitiated by the over-exploitation and greedy use of natural resources. The jeopardized abiotic spheres of nature will assuredly challenge smoother functioning of the biosphere (Yadav et al., 2018). During the course of time, fulfilling the livelihood security, farming too have emerged some environmental concerns. With modernization in developing nations, human are always fascinated towards energy driven mechanized farming. Farming practices are mainly dependent on the burning of fossil fuels to satisfy their energy requirement and contribute a major fraction of Greenhouse gases (GHGs) emission (Tjandra et al., 2016; Ashoka et al., 2017). Globally land use change is responsible for 10–12% of anthropogenic annual GHGs emission (IPCC, 2017). Positive feedback towards climate change from the traditional agricultural technologies compelled researchers to explore in details regarding their carbon footprint (CFy), energy and economic effectiveness. Rice being a staple food crop of India and rice-wheat (RW) system is the commanding one. During 2016 in India, rice cultivation emitted an estimated amount of 96.2 Mt CO₂-e (FAO, 2017). Hence, a noteworthy cut down of GHGs emission from farm activities can decelerate the pace of climate change (Liu et al., 2016; Parihar et al., 2018b). Henceforth under climate change era search for a sustainable crop and cropping system with cleaner production technologies is the need of the hour.

Under changing climate scenario, maize being a C₄ plant is a striking alternative for rice in north-western Indo-Gangetic Plains (IGP) region of India. Globally, maize is grown across wide agro-ecologies in 155 nations and is third most important cereal crop; it is often referred to as “Queen of cereals, back bone of America and miracle crop”. Nearly 31.0% of the maize grains are produced in the United State of America followed by China (24%), Brazil (8%) and India (2.2%) (Ranum et al., 2014). Economically maize cultivation is becoming less and less profitable in India because of increasing input costs; particularly cost involved in field preparation because of escalating diesel price. Recently, CA-based crop production practices comprising of minimum soil mechanical manipulation, proper soil cover and growing of different types of crops in cropping sequence helps to successfully reduce the cost of crop production and fuel requirement. In addition, CA practices provide ecological services for soil and environmental health improvement with lower carbon footprints. Worldwide, the area under CA is increasing due to the shortage of labour and escalating input prices and is practiced on 125 Mha. However, in India area under CA is limited to 1.5 Mha only (Bhan and Behera, 2014). It is well documented that fallow lands also contribute to GHGs emissions (Haque et al., 2015; Sander et al., 2018), therefore cropping in the fallow period (from May to June months) of existing cereal-based cropping systems can sequester atmospheric CO₂ in soil. Under such situation introduction of short-duration dual purpose summer season (May–June) grain legume (e.g. mungbean) have potential to get better soil and environment with additional profits (Yadvinder-Singh et al., 2011; Jat et al., 2014). Nutrient, energy & water are the key inputs in agricultural production systems. To seek out

maximum benefits, our management options must favor their highest recovery. Among all the nutrients, N is very dynamic in soil and plant system, as evident from lower N recovery (<50%) from applied fertilizer in cereal crops (Malhi et al., 2001; Chien et al., 2009). Further, under CA-based zero tillage (ZT) practices major soil property changes due to surface residue retention and consequently, the soil N dynamics gets altered. Thus divergent N management strategy must be advocated with residue retention (McConkey et al., 2002; Arora et al., 2010). With lesser soil organic matter decomposition under ZT with restricted mechanical soil disturbance, N mineralization gets reduced during initial 3–4 years of its adoption. When SOM content is low, retention of crop residues influences N immobilization and volatilization and hence N dynamics (Drinkwater et al., 2000; Yadvinder-Singh et al., 2005). Broadcasting of N on surface retained crop residues is an inefficient method as residue intercepts some fraction of fertilizer and favors N volatilization and microbial immobilization in presence of carbon-rich source (Thuy et al., 2008; Xu et al., 2010). Despite more favorable research findings of CA, its adoption at farmer's field is poor because of several reasons and the most important one is improper N management. Split application of traditional N fertilizer (like PU) for higher N-use efficiency (NUE) requires more labour and energy and reduces farm profitability. Moreover, under CA with surface residue retained condition, lack of farm machinery for subsurface drilling makes split application of urea more troublesome. Therefore, to enhance the farm profitability and fertilizer NUE of CA-based maize production systems one-time application of slow release N-fertilizer can be a better option to solve the problem of labour shortage under intensive fertilizer based agriculture.

After nutrient, ‘energy’ being the next significant input in agriculture for satisfying the food requirement of the growing population. The crop productivity is directly associated with energy inputs in different agricultural operations. The vital relationship between energy and farming system under existing intensive cereal-based cropping systems needs to be more emphasized, especially under resource-limited situation of Indo-Gangetic Plains (IGP) region of South Asia. Mechanization of conventional farming needs additional use of fuel energy (Chaudhary et al., 2006; Meena et al., 2017). Agricultural ecosystems can be assessed by energy budgeting and the production systems with greater energy efficiency in an agro-climate must be encouraged. Addressing the issues related to energy efficiency in Indian agriculture, the farming can be cheaper and cleaner with lower GHGs emission (Pishgar-Komleh et al., 2012). Thus, a framework of mitigation strategy with a co-optimization between lower energy use and emission cut off is needed, so that the global warming potential (GWP) is minimum to bring out the environmental sustainability. Hence, there is need to identify or develop energy efficient and cleaner crop production technologies, having lower carbon footprints in maize-based systems (Bojaca and Schrevens, 2010; Ittersum et al., 2008).

In the scenario of global climate change, the C-sequestration and low energy input farming are given paramount importance, so the present study was carried out for assessing the energy requirement, carbon footprint, and the economic feasibility of CA-based PB with and without residue management with integrated use of contrasting N sources in diversified maize systems.

The findings of our study brought an innovation towards sustainable and energy efficient production practices with lower GHGs emission in maize-based systems through an appropriate combination of diverse N sources and residue management options in permanent beds (PB). The data set generated would boost knowledge of researchers and will act as a pathfinder for policymakers towards the C-neutral CA-based maize farming systems for a clean environment.

2. Materials and methods

2.1. Climate and soil of study site

A field research trial was carried out during four successive years (2012–2016) at the same field of ICAR-Indian Institute of Maize Research farm New Delhi, India. Study place is situated at 28° 40' N, 77° 12' E & 228.6 m elevation. Yearly normal precipitation of this semi-arid area is 650 mm with warm and dry summer and chilly winters. The experimental site has alluvial origin, flat and well-drained sandy loam soil (Typic Haplustept) with, sand (641 g/kg), silt (169 g/kg) and clay (190 g/kg) with pH 7.8 EC 0.33 dS/m, respectively. The study was conducted in a fixed layout in all the 4-years. Imposed treatments and crop management practices were alike in all the years. Representative soil samples were taken in July 2012 at 0–30 cm soil layer by a 5.0 cm diameter auger. Soil samples for baseline analyses were obtained from 8 randomly chosen spots, and were blended to get four composite samples. Analysis of the composite soil samples reveals that soil had 4.63 g/kg of organic C, KMnO₄ oxidizable N 156.8 kg/ha (Subbiah and Asija, 1956), 0.5 M NaHCO₃ extractable P 14.1 kg/ha (Olsen et al., 1954), and 1 N NH₄OAC extractable K 153.3 kg/ha (Prasad, 1998).

2.2. Particulars of layout and crop based agro-techniques

The design of experiment was split-split-plot with 16-treatment combinations of 2-crop rotations [MMuMb and MWMb] as main-plot treatments, 2-tillage and residue management [PB–R, zero tillage permanent beds without residue and PB+R, zero tillage permanent beds with residue] as sub-plot and 4-nitrogen management [Un-fertilized, PU, SCU, and NCU] as sub-sub-plot treatments. Harvestable plots of 31.5 m² (7.5 × 4.2 m) size were replicated thrice. The fine points regarding treatments are depicted diagrammatically in Supplementary Fig. 1. Before starting of the experiment, the land was deep chisel ploughed and laser land leveled. During July 2012, beds were created newly with a bed planter, and the same was continued as permanent beds (PB) in succeeding time. The mid-furrow to mid-furrow widths of the beds were 67.5 cm, along with flat tops width of 37 cm, and furrow depth of 15 cm. Permanent beds were reshaped and simultaneously shown during the later years of experimentation in one pass of a multi-crop planter. One row of maize (cv. DHM-117), two rows of wheat (cv. HD 2967), mustard (cv. NRCDR-2) and mungbean (cv. Pusa Vishal) were sown on each raised bed.

Crop-based fertilizer doses (N:P₂O₅:K₂O) were applied in different crops @ 150:60:40 kg/ha, 90:40:30 kg/ha and 120:60:40 kg/ha for maize, mustard and wheat, respectively. In prilled urea treatments, 33% N dose and 100% P₂O₅ and K₂O doses were applied with the last operation of field preparation. Rest 67% N was applied to maize in 2-equal doses at 2-stages i.e. eight leaves (V₈) & tasseling (VT), and to wheat at first & third irrigation. Mustard was fertilized with 100% P and K along with 50% of PU-N at sowing and rest 50% N was top dressed at 1st irrigation. For both sulphur and neem coated urea treatments, 100% of N, P₂O₅ & K₂O were applied at seeding in all the crops, the sulphur coated urea used in the experiment was made in the laboratory and had 2% commercial grade sulphur coating with 44.16% N content. However, in NCU the commercial grade neem coated urea having 46% N content was used in the experiment. The detailed description about NCU is given in Supplementary text file 1. In the summer season mungbean crop, 18:46 kg/ha of N:P₂O₅ was applied at the sowing time. Mungbean

residues were applied @ 1.5 Mg dry residues/ha before first cropping season (rainy, 2012). During successive cropping seasons, approximately 1/3rd of available residues of maize (1.33–4.75 Mg dry residue/ha), mustard (2.53–4.80 Mg dry residue/ha), wheat (1.35–2.56 Mg dry residue/ha) and full amount of mungbean residues (2.24–4.81 Mg dry residue/ha) were retained in residue management treatments. The total amount of soil applied residue in various plots is specified in Table 1. For managing weeds, glyphosate was applied one week before planting of succeeding crops. After that, selective pre-emergence (PE) and post emergence (POE) herbicides like Atrazine as PE in maize, Pendimethalin as PE in mungbean, wheat and mustard and Clodinafop as POE at 28 to 32 DAS in wheat were applied. Rainy season maize was planted up to 15th of July and harvesting completed by end of October. Winter season wheat and mustard crops were planted up to mid-November and end of October, respectively and were harvested in the month of April and March, respectively. During all the years summer mungbean was planted till mid-April and till mid-June harvesting was completed.

2.3. System equivalent yield measurements

The ultimate criteria for an unbiased comparison of different treatment combinations are system productivity converted to maize equivalent yield (MEY) of diversified crops grown in the studied MWMb and MMuMb systems. The government of India fixed Minimum support prices (MSP) for mustard, wheat and mungbean were multiplied with their respective yields and were summed up. Further, this sum was divided by MSP of Maize to get the maize equivalent yield (Parihar et al., 2017b). Following Eq. (1) the MEY based on price was calculated and energy coefficients in place of prices were used to estimate the MEY based on energy by Eq. (2).

$$\text{MEY based on price (Mg/ha)} = \text{Maize yield} + [(\text{Mustard yield} \times \text{Mustard price}) \text{ or } (\text{Wheat yield} \times \text{Wheat price}) + (\text{Mungbean yield} \times \text{Mungbean price})] / \text{Maize price} \quad (1)$$

$$\text{MEY based on energy (Mg/ha)} = \text{Maize yield} + [(\text{Mustard yield} \times \text{Mustard energy coefficient}) \text{ or } (\text{Wheat yield} \times \text{Wheat energy coefficient}) + (\text{Mungbean yield} \times \text{Mungbean energy coefficient})] / \text{Maize energy coefficient} \quad (2)$$

where, yields are in Mg/ha and prices are in USD/Mg.

By multiplying MEY with protein content of maize grain biomass protein equivalent yield of particular crop rotation was computed. Nitrogen concentration was obtained by modified Kjeldahl's method (Jackson, 1958). The protein content of maize was estimated from Nitrogen concentration in grain by multiplying with 6.25 (Lindner, 1944; AOAC, 1990). As per the dietary recommendation for protein by Indian council of medical research 60 g adult person⁻¹ day⁻¹ was taken into consideration for computation of adult protein demand (ICMR, 1982).

2.4. Economic analysis

The economic net returns from combined treatments were computed separately considering the incurred variable cost only. Major input factors for crop production with variable cost involved are, use of energy (human and machinery) for diverse farming practices like residue management, seedbed preparation, sowing, nutrient and insecticide application, water management, harvesting and threshing and listed in Table 2 and Supplementary Table 1. The labour cost was computed with the minimum wage rate as per the Indian Labour Law on person-days basis for a hectare land, by taking into account 8 h to be equal to 1 person-day. Likewise, a tractor-drawn machine/implement time (h) necessary to complete a field operation was counted and expressed as hours per hectare. And the cost for different operations

Table 1
Estimated total amount of residue biomass inputs (Mg/ha) of preceding crop for succeeding crop grown in maize-mustard-mungbean and maize-wheat-mungbean sequences during different years of experimentation.

Treatments ^a	MMuMb					MWMb				
	2012-13	2013-14	2014-15	2015-16	Total	2012-13	2013-14	2014-15	2015-16	Total
<i>Tillage and residue management practices</i>										
PB–R	–	–	–	–	–	–	–	–	–	–
PB+R	7.6	9.2	10.3	10.5	37.6	6.3	8.0	9.0	9.3	32.6
<i>Nitrogen management practices</i>										
Un-fertilized	5.7	7.1	9.1	8.4	30.4	4.41	6.11	7.13	7.17	24.8
N through PU	8.5	9.8	9.2	10.6	38.1	6.85	8.20	9.54	9.82	34.4
N through SCU	7.9	8.9	11.7	11.1	39.7	6.89	8.89	9.99	10.21	36.0
N through NCU	8.4	10.8	11.3	11.8	42.3	7.05	8.74	9.34	9.92	35.0

^a PB–R: zero tillage permanent beds without residue retention; PB+R: zero tillage permanent beds with residue retention; PU: prilled urea; SCU: sulphur coated urea; NCU: neem coated urea.

was computed using time and diesel consumed for each field operation and diesel market price. Every input cost was summed up to work out the total variable cost (TVC) of crop production system. The economics of gross returns (GR) were computed by multiplying the economic output (grain/seed and straw/stover/stalk yields of each crop) with their individual prices. The net returns (NR) were computed by calculating the difference between GR and total variable cost (TVC) (NR = GR – TVC). The net returns of crop rotations were computed by totaling the net returns from all the component crops grown within a crop year (July–June) in a particular cropping system. Indian rupees (INR) were changed into USD by considering the average exchange rate of the individual year.

2.5. Computation of energy

Energy balances were assessed quantitatively in all the treatment combinations considering the differential requirement of inputs and management. All the inputs involved in crop production were noted systematically on daily basis. The energy involved in production as well as the application of inputs was taken from literature and are given in Table 3, which was used for calculating the energy input requirement. Than from physical unit to energy unit conversions were done. Energy output is mainly in terms of harvested grain/seeds and remaining crop residues. Energy coefficients for grains/straws were multiplied with their output amount to get net energy output, and later was used for flux computation (Table 3). Then various energy indices were computed for comparing imposed treatments like; energy productivity (E_p), energy use efficiency (EUE), specific energy (E_{sp}), energy

intensity (E_{IN}) and net energy were calculated by Eqs. (3)–(8) (Chaudhary et al., 2017).

$$\text{Energy input } (E_I) = \sum_{i=1}^n (I_1 + I_2 + \dots + I_n) \text{ (MJ/ha)} \quad (3)$$

where, $I_1, I_2 \dots I_n$, are energy involved in different inputs (MJ/ha)

$$\text{Energy output } (E_o) = \text{system productivity } (S_p) \times \text{energy coefficients } (E_c) \text{ (MJ/ha)} \quad (4)$$

where system productivity is in Mg/ha and energy coefficients in MJ/Mg

$$\text{Net energy} = E_o - E_I \text{ (MJ/ha)} \quad (5)$$

$$\text{EUE} = E_o / E_I \quad (6)$$

$$\text{Energy productivity } (E_p) = \sum_{i=1}^n (S_p / E_I) \text{ (kg/MJ)} \quad (7)$$

$$\text{Specific energy } (E_{sp}) = \sum_{i=1}^n (E_I / S_p) \text{ (MJ/kg)} \quad (8)$$

Table 3

Energy equivalents and emission factors in agricultural production in relation to present study.

Particulars	Units	Equivalent energy (MJ)	Emission factors (kg CO ₂ -e/unit)
<i>A. Inputs</i>			
a. Human labour (R) ^{a,b}			0.86
1. Adult man ^a	man-h	1.96	
2. Women ^a	women-h	1.57	
b. Diesel ^{a,b}	l	56.31	3.32
c. Farm machinery ^{a,b}	kg	62.70	3.32
d. Chemical fertilizer			
1. N ^{a,c}	kg	60.60	4.96
2. P ₂ O ₅ ^{a,c}	kg	11.10	1.35
3. K ₂ O ^{a,c}	kg	6.70	0.58
e. Chemicals			
1. Herbicides ^{a,c}	kg/l	254.45	6.30
2. Insecticides ^{a,c}	kg/l	184.63	5.10
f. Seed of crops ^{a,d}			1.22
1. Maize/wheat/mungbean ^{e,f}	kg	14.70	
2. Mustard ^g	kg	22.72	
<i>B. Outputs</i>			
1. Maize/wheat/mungbean grain/seed ^{e,f}	kg	14.70	
2. Mustard seed ^g	kg	22.72	
3. Stover/straw ^{e,f}	kg	12.50	

^a Mittal and Dhawan (1988).

^b Deng (1982).

^c Lal (2004).

^d Wang et al. (2015).

^e Parihar et al. (2017a).

^f Parihar et al. (2018a).

^g Yadav et al. (2018).

Table 2

Agricultural inputs and services used under different tillage, residue and nitrogen management practices on four year mean basis in maize-mustard-mungbean and maize-wheat-mungbean cropping systems.

Treatment ^a	Maize-mustard-mungbean		Maize-wheat-mungbean	
	PB–R	PB+R	PB–R	PB+R
Manpower (days)	97	103	107	113
Seed (kg/ha)				
Maize	20	20	20	20
Mustard	5	5	5	5
Wheat	100	100	100	100
Mungbean	30	30	30	30
Fertilizer (kg/ha)				
Nitrogen	258	258	288	288
Phosphorus	146	146	166	166
Potassium	70	70	80	80
Chemical				
Insecticides (kg/ha)	2	2	2	2
Herbicides (kg/ha)	4	4	5	5
Irrigation diesel (l/ha)	47.9	46.3	52.6	50.6

^a PB–R: zero tillage permanent beds without residue retention; PB+R: zero tillage permanent beds with residue retention.

Table 4

Effect of tillage, residue and nitrogen management practices on four year mean basis system productivity, cost of cultivation, gross return and benefit cost ratio of maize-mustard-mungbean (MMuMb) and maize-wheat-mungbean (MWMB) cropping systems.

Treatment*	System productivity (MEY Mg/ha by price)		Cost of cultivation (USD/ha)		Gross return (USD/ha)		BC ratio (net return/cost of cultivation)	
	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R
Cropping systems								
MMuMb	12.0 ^a	13.4 ^a	946	1071	2736 ^a	3064 ^a	1.88 ^a	1.85 ^a
MWMB	11.9 ^a	13.3 ^a	1013	1160	2762 ^a	3098 ^a	1.71 ^b	1.66 ^b
Nitrogen management practices								
Un-fertilized	8.1 ^c	9.5 ^c	933	1042	1873 ^c	2201 ^c	1.01 ^c	1.12 ^c
N through PU	13.2 ^{ab}	13.8 ^b	1021	1165	3046 ^{ab}	3183 ^b	1.98 ^b	1.74 ^b
N through SCU	12.9 ^b	14.9 ^a	984	1126	2972 ^b	3430 ^a	2.02 ^b	2.05 ^a
N through NCU	13.5 ^a	15.3 ^a	979	1130	3104 ^a	3510 ^a	2.17 ^a	2.11 ^a

* PB–R: zero tillage permanent beds without residue retention; PB+R: zero tillage permanent beds with residue retention; PU: prilled urea; SCU: sulphur coated urea; NCU: neem coated urea. Means followed by a similar uppercase letter within a column are not significantly different (at $P < 0.05$) according to Least significant difference test.

$$\text{Energy intensity (E}_{IN}) = \sum_{i=1}^n (E_o/\text{COC}) \text{ (MJ/USD–ha)} \quad (9)$$

where COC is the cost of cultivation (USD/ha).

2.6. Carbon footprint (CF)

Impact of residue & N-management practices were analysed by computing the CF on ecology-based spatial and yield-scale. Ecology-based spatial CF is the whole quantity of GHGs (CO_2 and N_2O) emitted in whole cropping cycle as CO_2 equivalents (CO_2e) (Pratibha et al., 2016). Methane is produced in anaerobic soils where microbe has not accessible to oxygen as electron acceptor. Under such conditions, CO_2 acts as an electron acceptor and converted to CH_4 . Generally the redox potential of soil must be lowered to -0.2 V before methane is produced, but in the current study from seeding to harvesting the redox potential of the soil remained higher i.e. more aerobic than the condition favorable for methane emission (Brzezińska et al., 2012), thus only CO_2 and N_2O gases were taken into consideration. Additionally, there was no on-farm burning of any type of crop biomass. The CO_2 and N_2O emitted from the field were changed into a common unit of CO_2e by multiplying GWP potential of 1 & 298, respectively (Kirschbaum, 2014). Established emission coefficients from literature (Deng, 1982; Wes and Marland, 2002; Lal, 2004; Wang et al., 2015) were taken to convert the extent

of field operation and applied inputs to their respective equivalent emissions. This included all the factors having GHGs emissions involved in the production and use of all the inputs.

Emission factor (0.01) for N_2O emissions were multiplied with the quantity of N applied from fertilizer and crop residues, to get $\text{kg N}_2\text{O–N}$ emitted/kg N input and represented in Eq. (10) (Tubiello et al., 2015).

$$\text{N}_2\text{O emissions} = \text{Quantity of external N applied in kg/ha} \times 0.01 \times 1.571 \text{ (kg N}_2\text{O/year)} \quad (10)$$

Factor 1.571 is the conversion of N to N_2O (44/28).

GWP of emitted CO_2 and N_2O was computed by using Eq. (11):

$$\text{GWP} = (\text{emitted N}_2\text{O} \times 298) + \text{emitted CO}_2 \quad (11)$$

Carbon-footprint was computed with Eqs. (12) & (13) (Pandey and Agrawal, 2014):

$$\text{CFs} = \sum_{i=1}^n \text{GWP (kg CO}_2\text{–e/ha)} \quad (12)$$

where CFs is carbon-footprint per unit area

$$\text{CFy} = \frac{\text{CFs}}{\text{System productivity}} \text{ (kg CO}_2\text{–e/Mg)} \quad (13)$$

where CFy is carbon-footprint per unit yield, system productivity is in Mg/ha.

2.7. C-output, c-efficiency (CE), c-sustainability index (C_{SI}) and c-efficiency ratio (CER)

Crop accumulated photosynthates represent total C output and are calculated by multiplying their yield with their respective average C content in biomass. The C content in biomass of maize, wheat, mustard and mungbean were estimated like 41.4%, 38.7%, 34.8% and 42.5%, respectively (Parihar et al., 2018a). CE represents C-output to C-input ratio, whereas C_{SI} represents the ratio of the difference between C-output and C-input with C-input (Chaudhary et al., 2017; Lal, 2004). CER was computed using Eq. (14) (Chaudhary et al., 2017):

$$\text{CER} = \text{GY (in terms of C)/CEE} \quad (14)$$

where: CER: carbon efficiency ratio; GY: grain yield in term of carbon (Mg C); CEE: carbon-equivalent emissions.

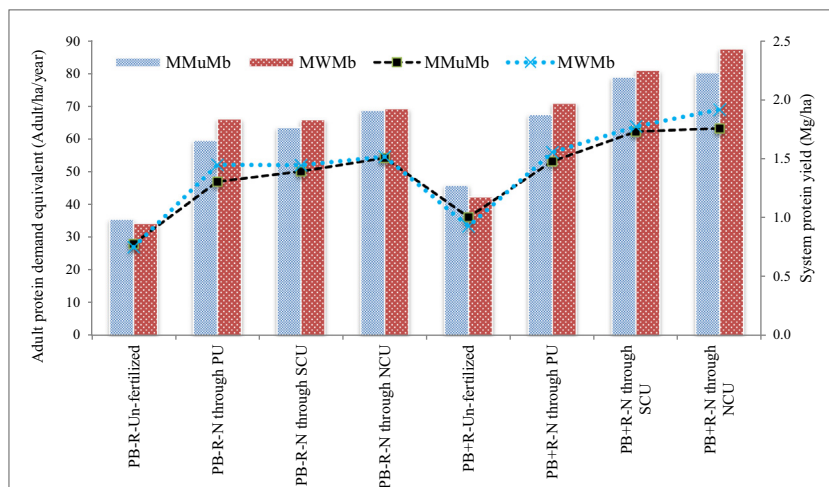


Fig. 1. Adult protein equivalent (bar graph) and protein equivalent yields (line graph) of maize-mustard-mungbean (MMuMb) and maize-wheat-mungbean (MWMB) cropping systems subjected to interactive effect of different tillage, residue and nitrogen management practices.

Table 5
Effect of tillage, residue and nitrogen management practices on four year mean basis energy (MJ/ha) utilization pattern in different operations of maize-mustard-mungbean (MMuMb) and maize-wheat-mungbean (MWMB) cropping systems.

Treatment ^a	Land preparation and sowing		Residue application		Fertilizer application		Irrigation		Herbicide application		Plant protection		Harvesting/threshing		Total input energy	
	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R
Cropping systems																
MMuMb	2532	2532	0	113,604	14,308	14,308	5436	5256	1035	1035	383	383	2582	2582	26,276	139,700
MWMB	3937	3937	0	97,830	15,888	15,888	7284	6946	1298	1298	379	379	2019	2019	30,805	128,298
Nitrogen management practices																
Un-fertilized	3234	3234	0	83,741	1603	1603	6360	6101	1167	1167	381	381	2301	2301	15,046	98,527
N through PU	3234	3234	0	109,102	19,602	19,602	6360	6101	1167	1167	381	381	2301	2301	33,044	141,887
N through SCU	3234	3234	0	113,735	19,594	19,594	6360	6101	1167	1167	381	381	2301	2301	33,036	146,512
N through NCU	3234	3234	0	116,291	19,594	19,594	6360	6101	1167	1167	381	381	2301	2301	33,036	149,068

^a PB–R: zero tillage permanent beds without residue retention; PB+R: zero tillage permanent beds with residue retention; PU: prilled urea; SCU: sulphur coated urea; NCU: neem coated urea.

2.8. Statistical analysis

The ANOVA for a split-split design was computed by using the procedure of GLM (SAS Institute, Cary, NC) to find out the statistically significance between the treatments. Comparison between treatments was done with the help of LSD values at $P < 0.05$ (Gomez and Gomez, 1984).

3. Results and discussion

3.1. System productivity

The cropping sequence and N management practices had significant ($P < 0.05$) effect on MEY, protein equivalent yield (PEY) and adult protein equivalent (APE) in various residue management options (Table 4 and Fig. 1). Both the cropping systems (MMuMb and MWMB) remained at par with respect to yield within same tillage and residue management practices. However, crops planted on PB with residue registered 11.7% increase in system productivity compared to PB–R. Highest PEY (1.91 Mg/ha) and APE (87.4 adult/ha/year) were registered in MWMB under PB+R and N through NCU (Fig. 1). Among N management treatments, highest system productivity was recorded in N through NCU in PB+R and PB–R being at par with N through PU under PB–R and N through SCU under PB+R. N management through Neem coated urea (NCU) recorded 2.3 and 10.9% higher system productivity compared

with non-coated prilled urea plot under PB–R and PB+R, respectively. In general, the superiority of coated urea materials over PU is due to the slow release of nitrogen through the coating, synchronized with the nitrogen need of the growing plants (Carreres et al., 2003; Cong et al., 2010). Nitrogen is released slowly and is absorbed and utilized by the plants effectively, hence with minimization of losses; crop use increases and simultaneously the system productivity. Neem oil extracted from seed kernels contains various kind of bitter, especially the meliacins that have been identified in retarding the process of nitrification of Urea. The biomolecules having antibacterial action against Gram-negative and Gram-positive microorganisms act as an active Nitrification Inhibitors (Biswas et al., 2002; Kumar et al., 2007). In this way, NCU maintained superiority over other coated materials due to its nitrification inhibiting character which suppressed the rate of formation and leaching loss of N as NO_3^- . Neem cake has acidic properties which also retarded the volatilization loss of NH_3 through reducing the alkalinity of the medium in the immediate vicinity of urea prills. Gagnon et al. (2012) and Sanjay-Kumar et al. (2015) had also similar finding for the effectiveness of coated fertilizer towards a higher yield of ZT maize.

3.2. Economics

Cost of cultivation and economic returns from different tillage and residue management practices are shown in Table 4. The mean cost of cultivation of all the years in MWMB cropping system was marginally greater from that of MMuMb (Table 4). It was 67 and 89 USD/ha higher

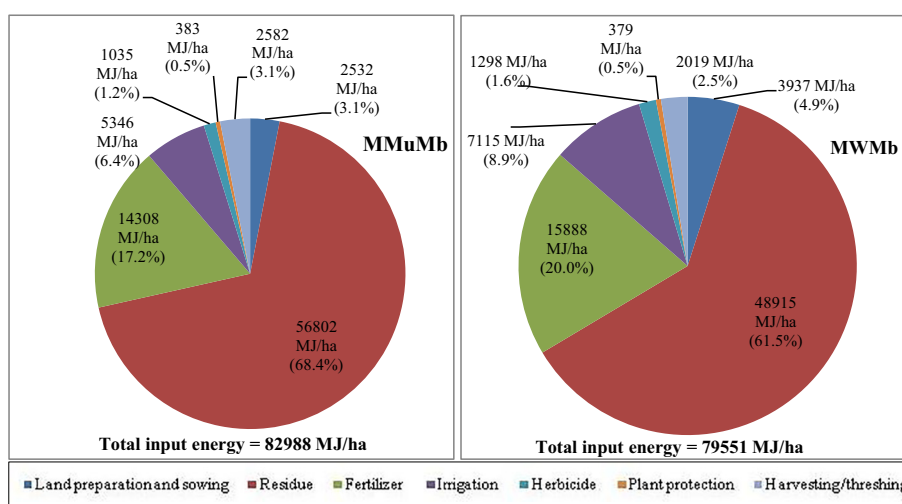


Fig. 2. Share of different farming operations in energy input of maize-mustard-mungbean (MMuMb) and maize-wheat-mungbean (MWMB) cropping systems under tillage, residue and nitrogen management practices.

Table 6

Effect of tillage, residue and nitrogen management practices on four year mean basis system productivity, energy output, net energy, energy use efficiency, energy productivity and energy intensity of maize-mustard-mungbean (MMuMb) and maize-wheat-mungbean (MWMB) cropping systems.

Treatment*	Energy input (MJ/ha)		Energy output (MJ/ha)		Net energy (MJ/ha)		Energy use efficiency		Energy productivity (Kg/MJ)		Specific energy (MJ/Kg)		Energy intensity (MJ/USD-ha)		System productivity (MEY by energy-Mg/ha)	
	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R
Cropping systems																
MMuMb	26,276	139,700	387,058 ^a	425,155 ^a	360,782 ^a	285,455 ^a	15.6 ^a	3.05 ^a	0.479 ^a	0.096 ^b	2.1 ^b	10.4 ^a	408 ^a	396 ^a	8.2 ^b	9.2 ^b
MWMB	30,805	128,298	355,206 ^b	392,336 ^b	324,401 ^b	264,038 ^a	11.9 ^b	3.04 ^a	0.396 ^b	0.103 ^a	2.6 ^a	9.7 ^b	349 ^b	336 ^b	9.4 ^a	10.5 ^a
Nitrogen management practices																
Un-fertilized	15,046	98,527	259,932 ^c	296,995 ^c	244,886 ^c	198,468 ^c	17.6 ^a	3.01 ^a	0.543 ^a	0.097 ^b	1.9 ^c	10.3 ^a	280 ^c	286 ^c	5.6 ^c	6.6 ^d
N through PU	33,044	141,887	410,336 ^{ab}	425,110 ^b	377,292 ^{ab}	283,223 ^b	12.5 ^{bc}	3.00 ^a	0.402 ^{bc}	0.098 ^b	2.5 ^{ab}	10.3 ^a	402 ^b	366 ^b	10.1 ^a	10.2 ^c
N through SCU	33,036	146,512	396,664 ^b	451,660 ^a	363,628 ^b	305,148 ^a	12.1 ^c	3.08 ^a	0.393 ^c	0.102 ^a	2.6 ^a	9.8 ^b	404 ^b	403 ^a	9.5 ^b	11.1 ^b
N through NCU	33,036	149,068	417,597 ^a	461,216 ^a	384,561 ^a	312,148 ^a	12.8 ^b	3.10 ^a	0.410 ^b	0.103 ^a	2.5 ^b	9.8 ^b	428 ^a	409 ^a	10.0 ^a	11.4 ^a

* PB–R: zero tillage permanent beds without residue retention; PB+R: zero tillage permanent beds with residue retention; PU: prilled urea; SCU: sulphur coated urea; NCU: neem coated urea. Means followed by a similar uppercase letter within a column are not significantly different (at $P < 0.05$) according to Least significant difference test.

in PB–R and PB+R, respectively. The higher expenditure in MWMB was mainly because of higher seed, irrigation and fertilizer cost involved in wheat cultivation compared to mustard cultivation in MMuMb. Crop residue retention in PB increased the cost of cultivation by 125 and 147 USD/ha in MMuMb and MWMB, respectively compared to the cost incurred under PB–R. In India, crop residues are important livestock feeding materials; this makes it a costly component, so the cost of cultivation was higher in PB+R. The cost of cultivation under different N management practices varied from 933 and 1042 USD/ha in the unfertilized plot to 1021 and 1165 USD/ha in N through PU under PB–R and PB+R, respectively. Coated fertilizer treatments had the lower cost of cultivation than prilled urea treatment plots because of one-time application of former product compared to split application of later one.

In general, about 12% higher gross return under PB+R was computed as compared to PB–R, greater MEY under PB+R may be accounted for this. The economic outcome did not differ statistically between MMuMb and MWMB systems (Table 4). Gross returns were substantially increased from the unfertilized plot with different N management options, and followed the trend of N through NCU > PU > SCU > unfertilized under PB–R. However, this trend under PB+R was N through NCU > SCU > PU > unfertilized. The higher gross revenue under N through NCU was mainly because of greater system productivity than those under unfertilized plot (Table 4).

The benefit to cost ratio was estimated by dividing the net returns to the cost of cultivation. Unlike gross returns, calculated benefit to cost

ratio was highest in MMuMb (1.88 and 1.85) than MWMB (1.71 and 1.66) mainly because of higher system productivity as well as low cost of cultivation, particularly of the mustard crop. Furthermore, slightly lower B:C ratio was computed in PB+R in spite of higher gross returns largely due to lower in proportion to returns from residue management as compared to cost involved (Table 4). Application of N through NCU attained highest B:C ratio followed by N through SCU because of higher system productivity.

3.3. Energy use pattern and efficiency

The operation-wise energy use patterns were computed for both the systems (Table 5). Irrespective of residue retention the mean total energy of 82,988 and 79,551 MJ/ha was used in the MMuMb and MWMB rotations, respectively (Fig. 2). Largely, crop residues contributed highest energy input 68.4 and 61.5% in MMuMb and MWMB cropping system, respectively. Next to it, the major energy demanding operation is fertilizer application, it accounts for about 17.2% of total energy in MMuMb and 20.0% in MWMB. In similar ecology, Parihar et al. (2017a) described crop residue management as most energy demanding operation (71–89%) in maize-based cropping system. MWMB required 1405 MJ/ha more energy for land preparation and sowing compared to MMuMb. Similarly, irrigation operation in MWMB consumed about 1769 MJ/ha more energy than MMuMb. This was mainly because, wheat cultivation in MWMB cropping system required more irrigations than mustard. The energy consumption in various N

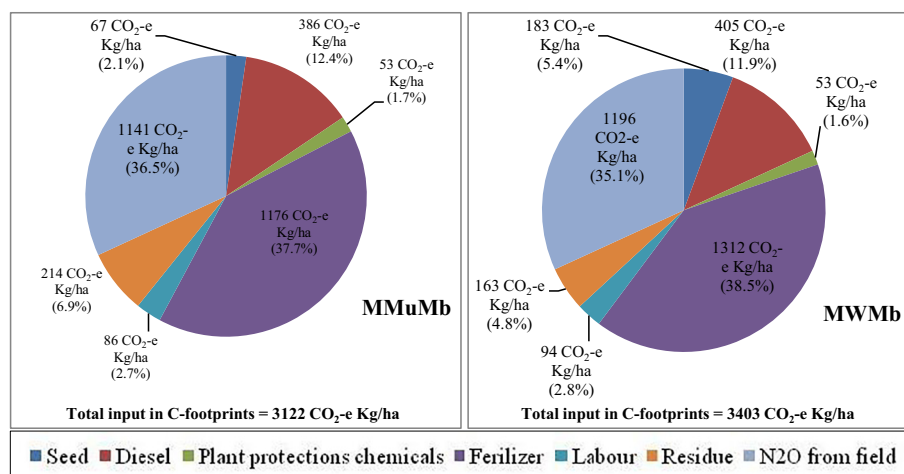


Fig. 3. Share of different inputs towards carbon footprints of maize-mustard-mungbean (MMuMb) and maize-wheat-mungbean (MWMB) cropping systems under various tillage, residue and nitrogen management practices.

Table 7
Effect of tillage, residue and nitrogen management practices on four year mean basis carbon footprints of maize-mustard-mungbean (MMuMb) and maize-wheat-mungbean (MWMB) cropping systems.

Treatment*	Carbon footprint (CO ₂ -e kg/ha)																	
	Diesel		Fertilizer		Plant protection chemicals		Seed		Labour		Residue		N ₂ O from farm		Total		CFy (CO ₂ -e kg/Mg)	
	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R
Cropping systems																		
MMuMb	388	383	1176	1176	53.1	53.1	67.1	67.1	83.0	88.2	0	428	927	1355	2695	3122	214 ^b	224 ^b
MWMB	410	400	1312	1312	53.1	53.1	183.0	183.0	91.6	96.8	0	326	1033	1359	3082	3403	246 ^a	244 ^a
Nitrogen management practices																		
Un-fertilized	399	391	151	151	53.1	53.1	125.1	125.1	85.1	90.3	0	315	84	399	898	1210	112 ^c	128 ^c
N through PU	399	391	1608	1608	53.1	53.1	125.1	125.1	90.3	95.5	0	385	1278	1664	3554	3937	268 ^b	285 ^a
N through SCU	399	391	1608	1608	53.1	53.1	125.1	125.1	86.9	92.0	0	401	1278	1680	3551	3949	275 ^a	265 ^b
N through NCU	399	391	1608	1608	53.1	53.1	125.1	125.1	86.9	92.0	0	406	1278	1685	3551	3954	264 ^b	259 ^b

* PB–R: zero tillage permanent beds without residue retention; PB+R: zero tillage permanent beds with residue retention; PU: prilled urea; SCU: sulphur coated urea; NCU: neem coated urea. Means followed by a similar uppercase letter within a column are not significantly different (at $P < 0.05$) according to Least significant difference test.

management practices was similar except the unfertilized plot (Table 5). Among various N management practices total energy requirement was highest in plots under N application through NCU (149,068 MJ/ha), followed by N through SCU (146,512 MJ/ha) > N through PU (141,887 MJ/ha) > unfertilized (98,527 MJ/ha) in PB+R practice.

The indices based on energy and system productivity like E_o , EUE, E_p and E_{sp} can describe and find the energy efficient farming system (Table 6). On an average, 31,852 MJ more energy was accumulated in the biomass of MMuMb (387,058 MJ/ha) than MWMB although having similar system productivity (MEY). Mustard being an oilseed crop accumulated higher energy in their seeds as compared to cereals. In the present study, MMuMb cropping system had higher net energy (360,782 vs. 324,401 MJ/ha), EUE (15.6 vs. 11.9) and energy productivity (0.479 vs. 0.396 kg/MJ) as compared to plots under MWMB in PB–R (Table 6). Alike trends were also reported by Parihar et al. (2017a). Among N management practices, N application through NCU had higher energy output and net energy compared to unfertilized plot under PB–R. However, EUE and energy productivity were higher in unfertilized treatment. The outcomes of present experiment are well supported by the findings of Goglio et al. (2014) and Pratibha et al. (2015). Nitrogen application through NCU enhanced crop productivity and accordingly the energy output and net energy. However, lesser energy input because of no fertilizer application in unfertilized plot describes increased EUE and energy productivity.

3.4. Carbon footprint and use efficiency

The data indicated that CO₂ emissions from fertilizer use (37.7% in MMuMb and 38.5% in MWMB) followed by N₂O based estimation,

contributed the maximum carbon footprints (Fig. 3). Different farming operations with use of machines and having diesel consumption i.e., from sowing to harvesting, have considerable CO₂ emission (386 kg CO₂-e in MMuMb and 405 kg CO₂-e kg/ha in MWMB) (Fig. 3). All the three N management practices had similar total carbon emission but N through PU (285 CO₂-e kg/Mg) and SCU (275 CO₂-e kg/Mg) computed highest CF under PB+R and PB–R, respectively (Table 7).

In general, slightly higher C input and output were observed in PB+R than PB–R irrespective of treatments. Our observations are in parallel to Choudhary et al. (2017), with greater carbon input in residue retained than residue removed plots in both conventional tillage and zero tillage systems. C-input and C-output varied among the crop rotations but not significantly. MWMB cropping system required higher C input (841 and 928 kg/ha) and output (11,783 and 13,037 kg/ha) as that of MMuMb (Table 8). The higher carbon consumption in MWMB than MMuMb was because of higher fertilizer dose in former than latter. Decreasing the carbon emission from the applied C-input increases use efficiency of C-rich inputs and helps in decelerating the pace of anthropogenic induced GHGs emissions (Lal, 2004; Parihar et al., 2018a; Yadav et al., 2018). Averaged across four years, carbon efficiency (20.0 and 17.5), CSI (19.0 and 16.5) and carbon efficiency ratio (8.4 and 7.6) were greater in MMuMb rotation than MWMB (Table 8). The superior value of CSI and CE in MMuMb was because of lower C input with lower C output (grain yield). Application of nitrogenous fertilizer augmented the C input (1074–1078 vs. 330 kg/ha) and output (13,434–14,609 vs. 9283 kg/ha) in residue management systems as compared to unfertilized treatments. Nitrogen application through NCU had significantly ($P < 0.05$) higher carbon outputs because of higher yield. However, carbon efficiency, CSI and carbon efficiency

Table 8
Effect of tillage, residue and nitrogen management practices on four year mean basis carbon input, carbon output, carbon efficiency, carbon sustainability index and carbon efficiency ratio of maize-mustard-mungbean (MMuMb) and maize-wheat-mungbean (MWMB) cropping systems.

Treatment*	Carbon input (kg/ha)		Carbon output (kg/ha)		Carbon efficiency		Carbon sustainability index		Carbon efficiency ratio	
	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R	PB–R	PB+R
Cropping systems										
MMuMb	735	852	11,659 ^a	12,757 ^a	20.0 ^a	17.5 ^a	19.0 ^a	16.5 ^a	8.4 ^a	7.6 ^a
MWMB	841	928	11,783 ^a	13,037 ^a	17.0 ^b	16.3 ^b	16.0 ^b	15.3 ^b	7.0 ^b	6.9 ^b
Nitrogen management practices										
Un-fertilized	245	330	8207 ^c	9283 ^c	33.8 ^a	28.1 ^a	32.8 ^a	27.1 ^a	13.8 ^a	11.9 ^a
N through PU	969	1074	13,049 ^a	13,434 ^b	13.5 ^b	12.5 ^c	12.5 ^b	11.5 ^c	5.7 ^b	5.3 ^c
N through SCU	968	1077	12,454 ^b	14,262 ^a	12.9 ^b	13.3 ^b	11.9 ^b	12.3 ^b	5.5 ^b	5.8 ^b
N through NCU	968	1078	13,174 ^a	14,609 ^a	13.7 ^b	13.6 ^b	12.7 ^b	12.6 ^b	5.8 ^b	5.9 ^b

* PB–R: zero tillage permanent beds without residue retention; PB+R: zero tillage permanent beds with residue retention; PU: prilled urea; SCU: sulphur coated urea; NCU: neem coated urea. Means followed by a similar uppercase letter within a column are not significantly different (at $P < 0.05$) according to Least significant difference test.

ratio were computed higher under unfertilized plot because of lower carbon input (Table 8).

4. Conclusions

Intensive agricultural production systems rely on fossil fuel burning for energy management and having a lion share in the energy input and GHGs emissions. There is a lack of information about the carbon and energy index of coated and non-coated nitrogen sources interacting with residue management in maize-based systems under CA-based permanent beds. Hence, the experimental finding enriched the existing science based knowledge regarding different indices of carbon and energy efficiency and profitability of contrasting N sources with aspect to coating in combination with residue management. Crop residue retention is a form of renewable energy input in CA-based diversified maize systems, registered 11.7% increase in system productivity. Despite having similar productivity in both the CA-based systems, MMuMb has higher B:C ratio, lower cost of production, and carbon footprints (~9% less than MWuMb) on spatial scale. In both the cropping systems major share of total energy input comes from renewable sources (i.e. crop residue-61–68%), followed by the fertilizer (17–20%). Fertilizer application has the highest (~38%) carbon footprint on a spatial scale in both the system. Among N management practices, neem coated urea treated plots had higher system productivity with lower carbon footprint (259–264 CO₂-e kg/Mg) than prilled urea and sulphur coated urea plots. Similarly with one time application of coated fertilizer treatments had the lower cost of cultivation than prilled urea treatment. Considering all the parameters, the study recommends that the CA-based MMuMb system with efficient N management through NCU is an environmentally safe, clean and energy efficient one, hence can reduce carbon footprints, will ensure food security (by satisfying protein requirement of 80.1 adults/ha) and mitigation of climate change i.e., the key sustainable development goals (SDGs). In aspects of carbon and energy efficiency the scope of N biofertilizer has immense importance, as it has the potential to replace a part of chemical N fertilizer and then farming will be more dependent on renewable sources. Therefore in future, the synergistic combinations of the more diverse N management options suitable for particular crop and cropping systems must be explored under CA to achieve the SDGs.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2019.01.425>.

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